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BLACK HOLES AND LOCAL DARK MATTER

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ABSTRACT

Two independent constraints are placed on the amount of dark matter in black holes contained in the galactic disk. Gas accretion by black holes leads to X-ray emission which cannot exceed the observed soft X-ray background. Second, metals produced in stellar processes that lead to black hole formation cannot exceed the observed disk metal abundance. Based on these constraints, it appears unlikely that the missing disk mass could be contained in black holes. A consequence of this conclusion is that at least two different types of dark matter are necessary to solve the various missing mass problems.

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I. INTRODUCTION

A number of dark matter problems have been brought to light. Dark matter appears on scales as large as the entire Universe, on scales of galactic halos (Faber and Gallagher, 1979), on scales of dwarf spheroidal galaxies (Aaronson, 1983; Faber and Lin, 1983; Lake and Schommer 1983), finally down to the scale of within a few parsecs of the solar system (Bahcall, 1984). Numerous candidates for the missing mass include remnants from the big bang (massive neutrinos, axions, monopoles, etc.) or baryonic matter (black holes, Jupiters, dust, etc.).

If we believe the cosmological density parameter $\Omega = 1$ ($\Omega = \rho/\rho_c$, where the critical density $\rho_c = 1.88 \times 10^{-29}\ h^2\ \mathrm{gcm}^{-3}$ and $h = H_o/(100\ \mathrm{km\ s}^{-1}\ \mathrm{Mpc}^{-1})$ is the scaled Hubble parameter), then a large fraction of the total mass of the Universe must be non-baryonic, since primordial nucleosynthesis requires the fraction of Ω due to baryons, Ω_B, to be less than 0.2 (Yang, etal. 1984). On the scale of small groups of galaxies, evidence indicates that $\Omega < 0.2$-0.3 (Davis and Peebles 1983) and may be all or largely baryonic. On galactic scales the mass-to-light ratios of spiral galaxies indicate that $\Omega > 0.05$ (Faber and Gallagher 1979). It has been argued (Hegyi and Olive 1983, 1985) that with the possible exception of black holes, galactic halos cannot be baryonic.

In this paper we examine yet another dark matter problem, the dark matter in the galactic disk. Bahcall (1984) determines the total mass density in the solar neighborhood by solving for the gravitational potential in the disk of the galaxy. If the dark matter is distributed about twice the luminous mass density. The identity of the local dark matter, with density $0.1\ M_\odot \mathrm{pc}^{-3}$, is the subject of this paper. The local dark matter cannot be dissipationless particles (like neutrinos or axions) since it must be confined to the disk. The most reasonable guess is that the local dark matter is baryons, but it is not clear what form the baryons take.

It should be emphasized that the local dark matter in the disk is a separate problem from the halo dark matter, and that the halo dark matter makes a negligible contribution to the disk. If we assume the halo density falls off as r^{-2} as deduced from rotation curves, $\rho_{HALO} = Ar^{-2}$, and the mass of the halo is $M_H = 4\pi A R_H$ where R_H is the maximum extent of the halo. A disk of radius R_D and height z contains a contribution to its mass from halo material of about $2\pi A\ z\ \ln(R_D/r_o)$ where r_o is a cutoff at the center of the galaxy. If we assume the total mass of the disk is a fraction f_D of the total halo mass, then the halo material contributes a fraction $z\ \ln(R_D/r_o)/2f_D R_H$ of the disk mass. This fraction is ~10% for reasonable values of the parameters, in agreement with Bahcall's models.

Black holes are a possible candidate for dark matter. If they are the primary component of the local dark matter, Bahcall finds that their mass density must lie in the range 0.07-$0.14\ M_\odot \mathrm{pc}^{-3}$. In our analysis we will assume $\rho_{BH} = 0.1\ M_\odot \mathrm{pc}^{-3}$, and, wherever appropriate, we will also give limits for Bahcall's minimum value, $\rho_{BH} = 0.07\ M_\odot \mathrm{pc}^{-3}$.

In this paper we consider two consequences of black holes as the dark matter in the galactic disk: the production of soft x-rays due to accretion of interstellar matter onto the black holes, and the production of metals in the disk during processes leading to formation of black holes. X-ray production depends upon the efficiency of converting accreted matter into radiation, and metal production depends upon the initial mass function of the black hole progenitors. The *limits we place on the radiation efficiency and on the initial mass function are outside the expected values, hence we conclude that black* holes are unlikely to be the local dark matter.

Before proceeding, it is useful to note that Bahcall, Hut, and Tremaine (1985) have shown that if the mass of the objects comprising the dark matter in the disk were greater than 2 $M_\odot$, they would disrupt weakly bound binaries in the disk.

II. ACCRETION ONTO BLACK HOLES

Black holes traversing the interstellar medium will accrete gas. We can derive an upper limit on the mass of black holes by requiring that the amount of radiation produced by accretion be less than the observed upper limits. The radiation efficiency, ϵ, is model dependent, but most estimates are in the range $\epsilon \approx 0.1$ (Meszaros 1975; Ipser and Price 1977; Rees 1977).

A black hole of mass M moving at supersonic velocity v through a medium of density n will accrete mass at a rate (Bondi 1952)

$$\dot{M} = 10^7 (M/M_\odot)^2 (n/\mathrm{cm}^{-3})(300\mathrm{kms}^{-1}/v)^3 \mathrm{~g~s}^{-1}. \quad (2.1)$$

The luminosity due to the accretion will be (we set $\hbar = c = 1$)

$$L = \epsilon \dot{M} \quad , \quad (2.2)$$

where ϵ is the efficiency of converting the accreting mass to radiation. If we take (Bahcall 1984) the local density to be $n = 1.85 \mathrm{~cm}^{-3}$ and the velocity to be $v \lesssim 20\mathrm{kms}^{-1}$, then

$$L = 8 \times 10^{31} \epsilon (M/M_\odot)^2 \mathrm{~erg~s}^{-1}. \quad (2.3)$$

Carr (1979) set a limit on the mass density of black holes in the disk by comparing the radiation emitted by the black holes to the background photon spectrum. If we assume that our galaxy is rather typical, the radiation energy density due to accretion will be $\rho_R \approx L t_U n^U_{BH}$, where $t_U = 6.5 \times 10^9 h^{-1}$ yrs is the age of a matter-dominated, $k = 0$ Universe and n^U_{BH} is the average number density of black holes in the Universe (which, of course, is less than the number density in the disk). We can express n^U_{BH} as

$$n^U_{BH} = \Omega_{BH} \rho_c M^{-1} \quad (2.4)$$

where Ω_{BH} *is the fraction of the critical density* (ρ_c) due to <u>disk</u> black holes. We take $\Omega_{BH} = \Omega_D/2$ where Ω_D is the total contribution to Ω from all disk matter. The value of Ω_D is limited by

$$\Omega_D = (M/L)_D L \rho_c^{-1} \approx (M/L)_D (1200h)^{-1} \quad (2.5)$$

with L the total luminosity density of the night sky, L =

$2 \times 10^8\ h\ L_\odot \mathrm{Mpc}^{-3}$ (Kirshner, Oemler, Schechter 1979). If we use Bahcall's value for $(M/L)_D = 3$ (Bahcall 1984) we have $\Omega_D \geq 2.5 \times 10^{-3}\ h^{-1}$, and hence $\Omega_{BH} \geq 1.25 \times 10^{-3}\ h^{-1}$. With this value for Ω_{BH} (hence n^U_{BH}), $\Omega_R = \rho_R/\rho_c$ is

$$\Omega_R = \frac{L\ t_U n^U_{BH}}{\rho_c} = 9.15 \times 10^{-6} h^{-1} \Omega_{BH} (M/M_\odot)\epsilon \tag{2.6}$$

If $\Omega_{BH} \geq 1.25 \times 10^{-3} h^{-1}$, then

$$\Omega_R \geq 1.14 \times 10^{-8} h^{-2} (M/M_\odot)\epsilon \quad . \tag{2.7}$$

A reasonable assumption for the spectrum of radiation from the accretion is that the bulk is in the soft X-ray region. The observational limit to the energy density in X-rays is $\Omega_X \leq 3 \times 10^{-8} h^{-2}$ (Silk 1973, Eichler and Solinger 1976), which requires

$$(M/M_\odot)\epsilon_X \leq 2.6 \tag{2.8}$$

where ϵ_X is the effeciency for producing soft X-rays. This limit is essentially the limit of Carr (1979). It is only interesting for $M \gtrsim 25\ M_\odot$, but we have seen that the existence of wide binaries implies $M \lesssim 2\ M_\odot$. However, the limit can be improved if we consider the contribution to the local X-ray flux, rather than the global flux, and take advantage of the fact that we live in a galaxy with nearby sources.

To model the photon emission, we will assume that a black hole radiates like a blackbody with a radiating surface at a radius R from the black hole. We expect R to be several Schwarzschild radii, so we write R in units of the Schwarzschild radius

$$R_S = 2GM \simeq 3\ (M/M_\odot)\ km \quad . \tag{2.9}$$

The spectrum of emitted radiation is unlikely to be blackbody. However, the X-ray limits improve with photon energy, and since for fixed luminosity any other reasonable spectrum will be harder than a blackbody, the assumption of a blackbody will lead to the most conservative limit. We also assume the radiation comes from a spherical surface. If the radiation comes from "hot spots" (rather than a spherical surface) it will contain more high energy photons for a fixed luminosity than a blackbody, so again the assumption of a blackbody will yield a conservative limit. Finally, we will consider two radii for the emitting surface.

The total luminosity of a black hole with radiating surface at R is

$$L = 9.14 \times 10^{29}\ (R/R_S)^2 (M/M_\odot)^2 (T/30\mathrm{eV})^4\ \mathrm{erg\ s^{-1}}, \tag{2.10}$$

and the differential luminosity will be

$$\frac{dL}{dE} = 1.7 \times 10^{35} \left(\frac{R}{R_S}\right)^2 \left(\frac{M}{M_\odot}\right)^2 \frac{E^3}{[\exp(E/T)-1]}\ \mathrm{erg\ keV^{4} s^{-1}}. \tag{2.11}$$

If the black hole is at a distance ℓ, the differential energy flux measured by a detector is

$$\frac{dF}{dE} = \frac{dL}{dE} \exp[-\tau(\ell,E)]/4\pi\ell^2, \tag{2.12}$$

where the absorption length, τ, is related to the absorption cross section, $\sigma_A(E)$, and the number density of absorbers, n_A, by

$$\tau(\ell,E) = \int_0^{\ell} n_A(r)\sigma_A(r)dr . \tag{2.13}$$

In calculating $\tau(\ell,E)$ we adopt the McKee-Ostriker (1977) three-phase model of the interstellar medium as used by Kolb and Turner (1984) for absorption of soft X-rays from neutron stars. We also use $\sigma_A(E) = 6 \times 10^{-23}(E/keV)^{-3}cm^2$ (Brown and Gould 1970; Ride and Walker 1977) for the absorption cross section. For soft X-rays, the photoionization of elements heavier than hydrogen is not important.

If we assume that the black holes are distributed about us to a distance R_M with a number density n_{BH}, then their total contribution to the differential energy flux per sr. is

$$\frac{dF}{dE} = \frac{n_{BH}}{4\pi} \int_0^{R_M} \frac{dL}{dE} \exp[-\tau(\ell,E)]d\ell . \tag{2.14}$$

In order for the black holes to account for the missing mass in the disk, $n_{BH} \simeq 10^{-1}(M_\odot/M)pc^{-3}$.

We will use a recent observation of McCammon, Burrows, Sanders and Kraushaar (1983) (MBSK) of the soft X-ray background flux to limit the radiation from the black holes. From the expected energy flux in Eq. (2.14) we can calculate a count-rate for MBSK

$$\Gamma_C = \int dF/dE\, A(E)dE \tag{2.15}$$

where $A(E)$ is a detector response function. For the relevant band of interest (the C-band - 0.13 keV $\leq E \leq$ 0.28 keV), $A(E)$ can be fit as (Kolb and Turner 1984)

$$A(E) = 1.33 \times 10^{11}\ (E-0.13keV)\ erg^{-1}cm^2sr\ keV^{-1}. \tag{2.16}$$

Using Eqs. (2.16), (2.14), (2.13), and (2.11) in Eq. (2.15) we have calculated the counting rate, Γ_C, as a function of the blackbody temperature for several values of R_3 and M.* If we require that the counting rate be less than 1/3 of the all sky average (there are significant regions with rates less than 1/3 average), we can limit the blackbody temperature, hence the luminosity. We can express this limit on the black hole luminosity as a limit on ϵ. The limit on ϵ, ϵ^{MAX}, is shown in Figure 1 for two values of the radius of the emitting surface.

It should be noted that ϵ is the total efficiency, not the efficiency in X-rays as the previous limit. If $R = 2R_S$, ϵ is greater than 10^{-2} only if $M < 1\ M_\odot$, while if $R = 5R_S$, ϵ is greater than 10^{-2}

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*Since absorption by the ISM is important, the counting rate is insensitive to R_M.

only for $M < 35\ M_\odot$. If $\varepsilon \approx 10^{-1}$ as expected, then either $R > 5\ R_S$ or $M \ll 1\ M_\odot$ -- either option is unlikely.[1]

[1]For a review, and references to the extensive literature on the subject of radiation in accretion onto black holes, see Shapiro and Teukolsky (1983).

III. BLACK HOLE FORMATION AND METALICITY

Black holes in the halo may be primordial (or at least pre-galactic) in origin. However the disk is a structure that has undergone dissipation and dissipationless black holes in the disk could not have formed before the disk. In this section we assume that the black holes in the disk were formed in the course of stellar evolution in the galaxy. In their formation there was probably an ejection of mass with a concomitant enrichment in metalicity of the interstellar medium. We can limit the possibility of black holes in the disk by requiring that their formation not lead to an overenrichment in metals.

All the limits we derive will depend on the mass of the black holes in the disk, which, in turn, depend on the initial mass function of the stars from which they were formed. Following Carr, Bond and Arnett (1984) we will take $8\ M_\odot$ as the minimum mass star which yields a black hole. For stars in the range $(8-100)\ M_\odot$, we assume that the production of the black hole is accompanied by a large amount of ejected matter (i.e. the mass of a black hole formed from stars in this range is much less than the initial mass). For stars more massive than $100\ M_\odot$ we will

simply assume that they may have formed black holes without any ejected matter. Thus our arguments relating to metalicity are only valid for stars less massive than $100\ M_\odot$. However for black holes with $M > 100\ M_\odot$ the arguments of the previous section and those of Bahcall, Hut, Tremaine already rule them out.

For stars in the mass range $(8-100)\ M_\odot$, we will assume that their distribution can be described by an initial mass function of the form

$$\phi(M) = M^{-(1+x)} \tag{3.1}$$

where ϕ is the number of stars formed per unit volume per unit mass. The slope of the initial mass function, x, is fitted to observations and depends on the mass range. In general the higher the mass range, the steeper the slope (larger x). Values for x have been quoted as: $x = 2.3$ for $(10-60)\ M_\odot$ (Miller and Scalo 1979); $x = 2.0$ (Lequeux 1979) and more recently $x = 1.6$ for $M > 20\ M_\odot$ (Garmany, Conti and Chiosi 1982). We will assume a single value for x in the range $(8-100)\ M_\odot$ which enhances the low mass end of the spectrum relative to the case with smaller x for smaller masses.

We can derive a lower limit to the slope of the initial mass function by requiring that the overall metalicity Z in the disk not exceed 2.5% (one could actually argue for $Z < 2\%$). We calculate the metalicity produced by stars in the range $(8-100)\ M_\odot$ by taking the mass fraction of metals ejected by the star (Arnett 1978) and integrating over the initial mass function. The overall metalicity is defined as

$$Z = \rho_m/\rho_o \tag{3.2}$$

where ρ_m is the mass density of metals and ρ_o is the total observed (not including black holes). If 50% of the disk is made of black holes of mass (1-2)$M_\odot$ which formed from stars of mass greater than 8$M_\odot$, we are forced to assume that essentially all of the disk has gone through stellar processing at least once. Thus the abundance of metals will be (for a given initial stellar mass)

$$\rho_m = (M_{ej}/M)\rho_i \tag{3.3}$$

where (M_{ej}/M) is the fraction of the initial stellar mass which is ejected in the form of metals and ρ_i is the fraction of the mass density processed by black holes. For (M_{ej}/M), we use the calculation of Arnett (1978) for the mass range 8-100 $M_\odot$. In Table 1 we list Arnett's values of M_{ej}/M. If the density which is eventually to be left over in the form of black holes is comparable to the observed density, then

$$\rho_i \sim 2\rho_o \sim 2\rho_{BH} \tag{3.4}$$

and

$$Z(M) = \rho_m/\rho_o = (M_{ej}/M)\ 2(\rho_{BH}/\rho_o) \sim 2(M_{ej}/M) \tag{3.5}$$

We then integrate Eq. (3.5) over the initial mass function to give

$$Z = \int Z(M)\phi(M)dM \tag{3.6}$$

Our results for Z as a function of the slope of the initial mass function are shown in Figure 2. We see that for $Z < 2.5\%$ we have $x > 6.7$. This is to be compared with the expected values given earlier $x \lesssim 2.3$. (For $\rho_{BH} = 0.07$, the limit becomes $x > 5.2$)

We emphasize that we do not expect that the initial mass function for black hole progenitor stars to differ greatly from that of Pop. I stars. These black holes must have formed in the disk in situations not very different than those presently observed. One cannot in this case argue that black holes were formed by Population III stars whose mass function was very different than Population I stars, as could be the case for halo objects. Therefore, low mass black holes that formed from progenitor stars in the mass range (8-100) $M_\odot$ cannot provide the dark matter in the disk.

In conclusion, we have considered the possibility that the dark matter in the disk consists of black holes formed in the course of galactic stellar evolution. Examination of two observational consequences of the black hole hypothesis -- radiation from gas accretion and metal production in the formation -- lead us to conclude that it is unlikely that black holes are the local dark matter. We have recently learned that J. McDowell (1985) has also examined the role of black holes in the disk. Note that our considerations of the consequences of black holes would also apply to neutron stars. Radiation is produced in accretion onto neutron stars, and metals are produced during neutron star formation.

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TABLE 1

Metal Production in Black Hole Formation

$M/M_\odot$	M_{ej}/M*
10	5×10^{-3}
12	0.047
16	0.125
22	0.164
28	0.24
35	0.30
50	0.35
75	0.31
95	0.42

* Taken from Arnett (1978).

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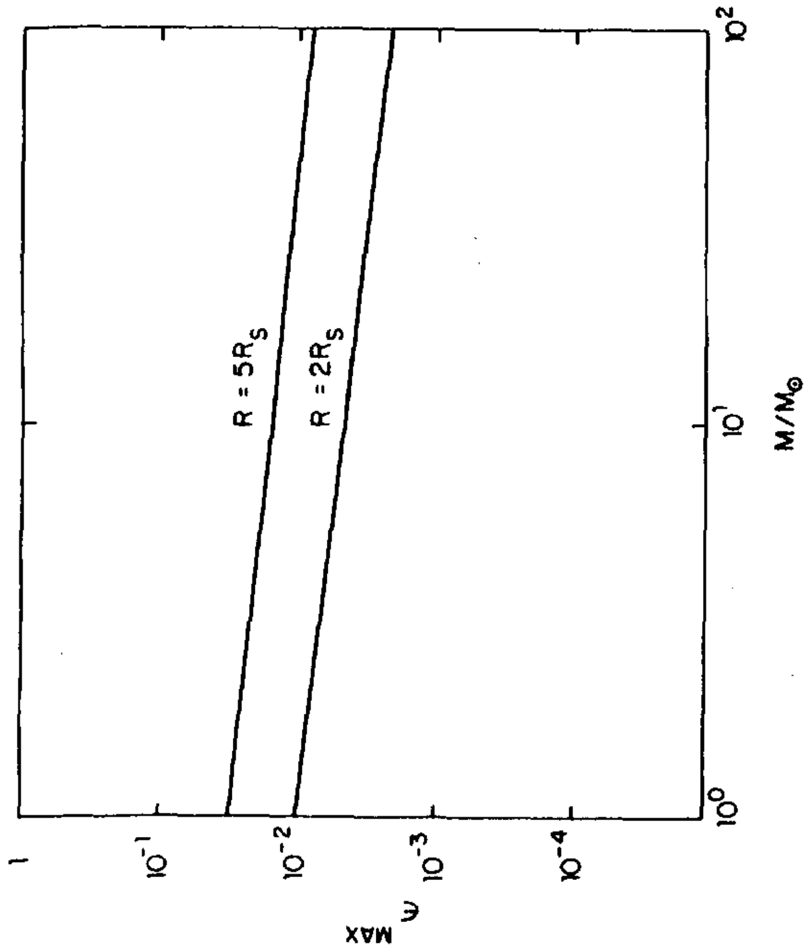

Figure 1: The maximum value of ϵ as a function of M for two values of R.

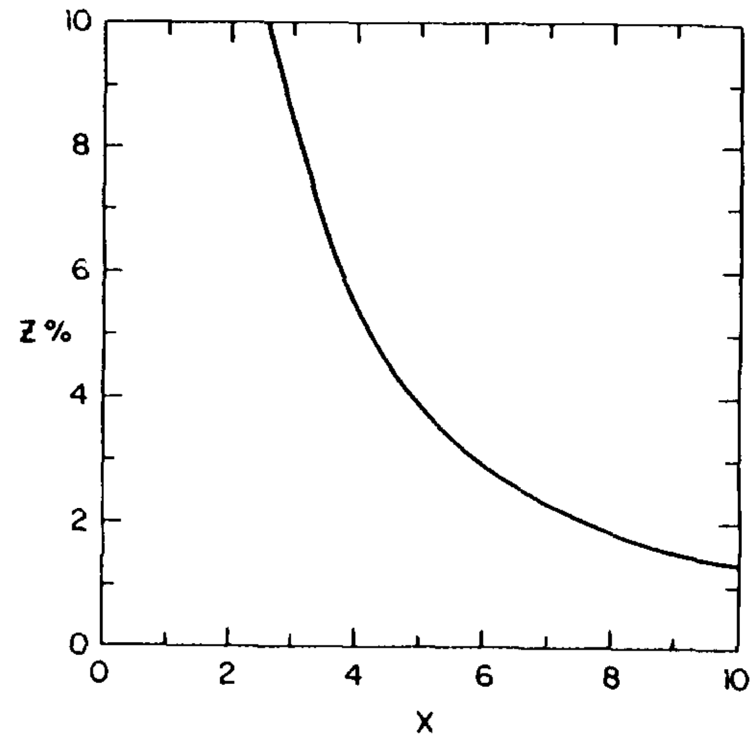

Figure 2: The metalicity as a function of the slope of the initial mass function.